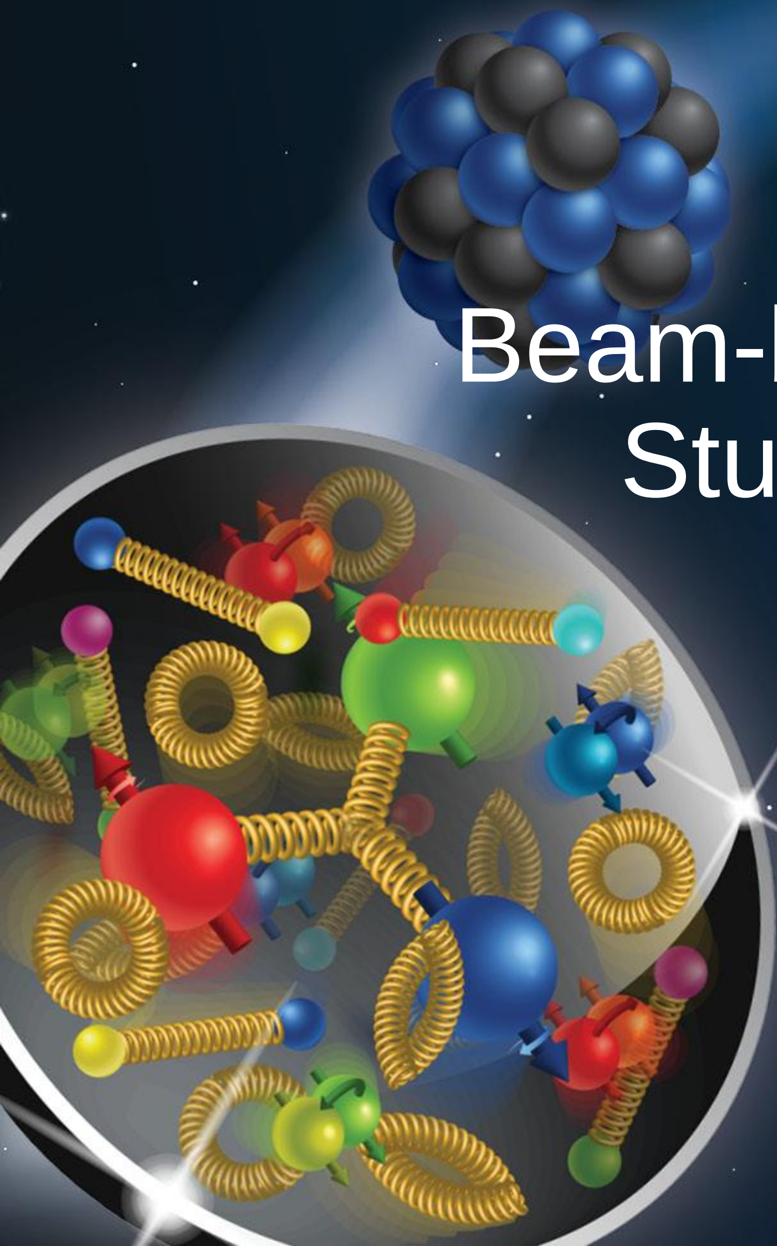


# Beam-beam Simulation Study for eRHIC

EIC Collaboration Meeting, ANL, Oct. 9-11, 2019

Yun Luo for eRHIC beam-beam study team

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

# Beam-beam studies for eRHIC

**Simulations to confirm / verify new beam-beam related design parameters**

1) crossing angle from 22mrad to 25mrad

2) proton ring harmonic number from 360 to 315

3) bunch filling pattern and long-range BB  4) proton crab cavity frequency choosing

**Pre-CDR writing and update**

1) re-did all strong-strong simulation with version 6.1 parameters

2) added new results of weak-strong simulation with crabbed collision

**Beam dynamics with crabbed beam-beam interaction**

1) determined particle stability with different longitudinal amplitudes

2) diffusion rate calculation        3) synchro-betatron resonance

4) proton / electron tune scans  5) effects of artificial static and random noises

**Simulation methods and algorithms**

1) consolidate weak-strong simulation method

2) modified weak-strong simulation  3) converted  BBSS to MPI code

4) dependences of numerical noises in strong-strong simulation

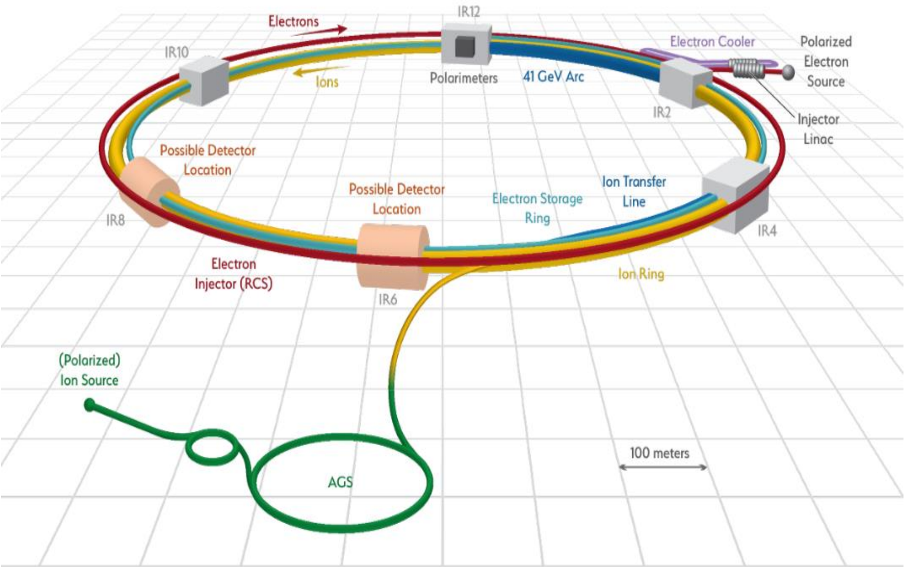
**FOA Lab 18-1848 project:  Development and test of simulation tools for EIC BBI**

1) implemented nonlinear truncated Taylor map tracking and symplectic tracking  methods

2) implemented new Poisson solver  into BB3D: spectral method

# Machine and beam parameters

eRHIC schematic layout




V6.1 beam-beam related parameters

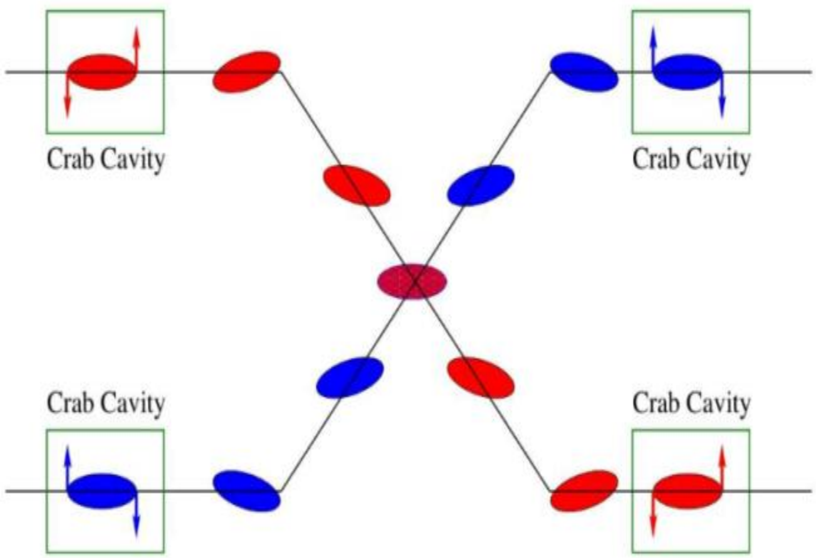
| Parameter | proton | electron |
|---|---|---|
| Ring circumference [m] | 3833.8451 | |
| Particle energy [GeV] | 275 | 10 |
| Lorentz energy factor $\gamma$ | 293.1 | 19569.5 |
| Bunch population [$10^{11}$] | 1.04 | 3.44 |
| RMS emittance (H,V) [nm] | (16.1, 8.5) | (20.0, 4.9) |
| $\beta^*$ at IP (H, V) [cm] | (90, 5.9) | (72, 10.2) |
| RMS bunch size $\sigma^*$ at IP (H, V) [$\mu$m] | (120, 22) | |
| RMS bunch length $\sigma_l$ at IP [cm] | 7 | 2.0 |
| RMS energy spread [$10^{-4}$] | 6.6 | 5.5 |
| Transverse tunes (H,V) | ( 0.310, 0.305) | ( 51.08, 48.06) |
| Synchrotron tune | 0.01 | 0.069 |
| Longitudinal radiation damping time [turn] | - | 2000 |
| Transverse radiation damping time [turn] | - | 4000 |

- The protons and electrons collide at IP6 and IP8. Each proton bunch only collides a particular electron bunch once a turn.
- The H/V beam-beam parameters for proton is 0.015/0.005. The H/v beam-beam parameters for electron are 0.10/0.76.

# Beam-beam with crabbed collision

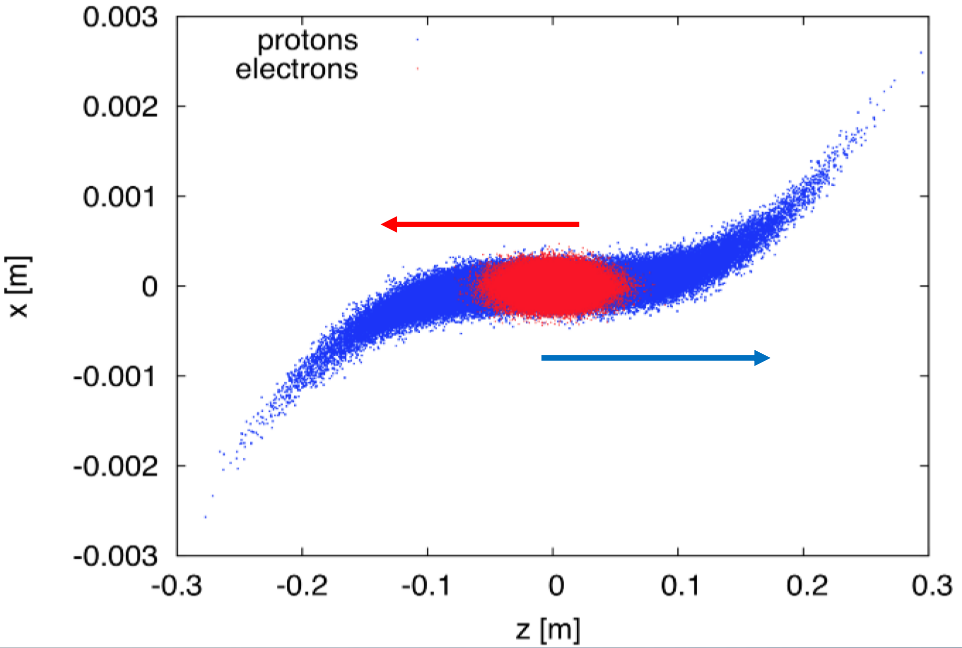
- To compensate the luminosity loss with a crossing angle 25 mrad, crab cavities are used for both rings.
- Due to finite wave length of crab cavities, protons in the bunch head and tail are not perfectly crabbed. Beam-beam interaction may generate synchro-betatron resonance and/or even head-tail instability.

25mrad full crossing angle




Local crabbing scheme

394MHz CC used in this example

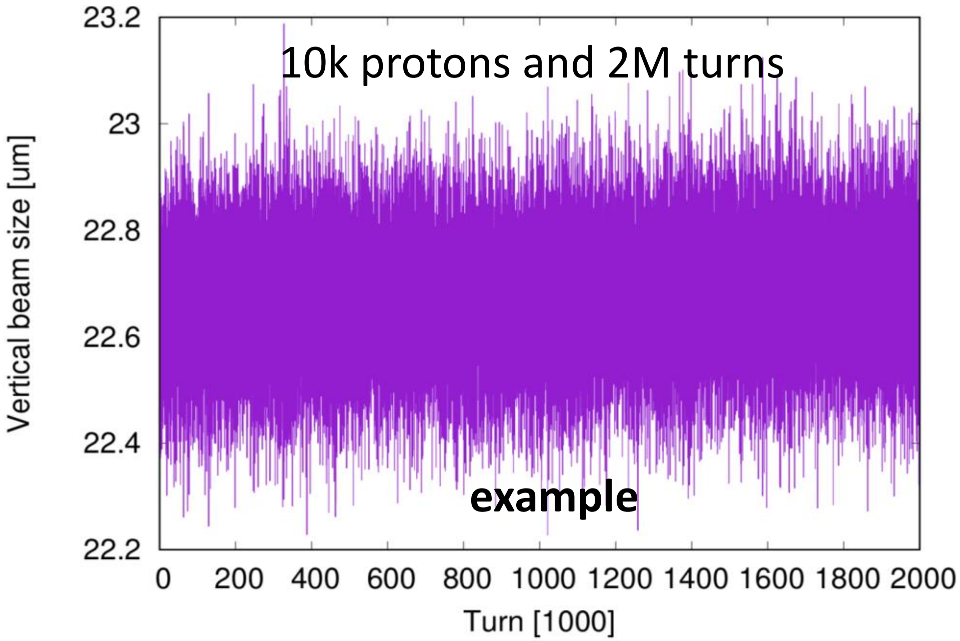


# Simulation methods and algorithms

**Weak-strong Simulation**

One bunch is treated as rigid bunch, another represented by macro-particles. Analytical beam-beam force is applied.

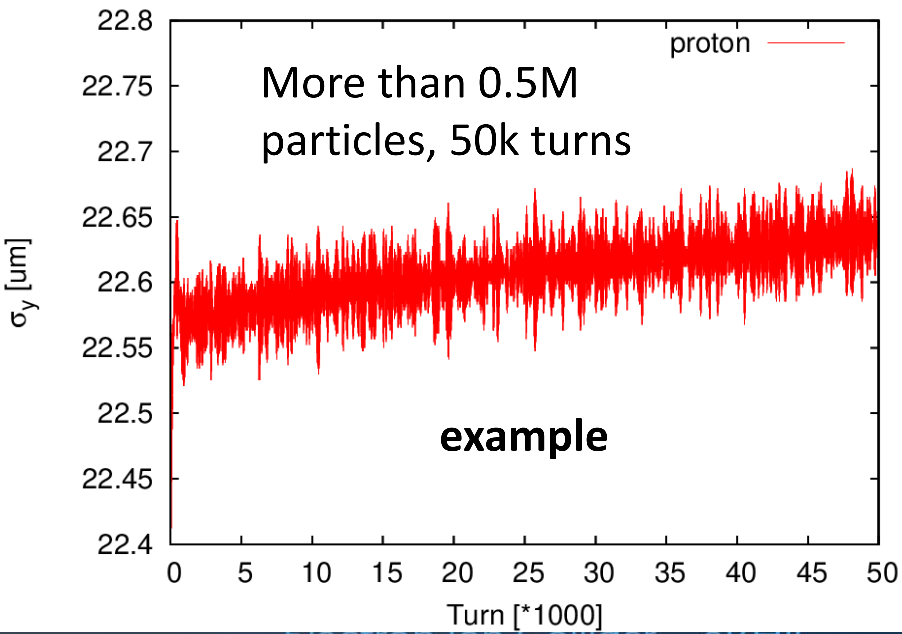
**Codes: SimTrack**




**Strong-strong simulation**

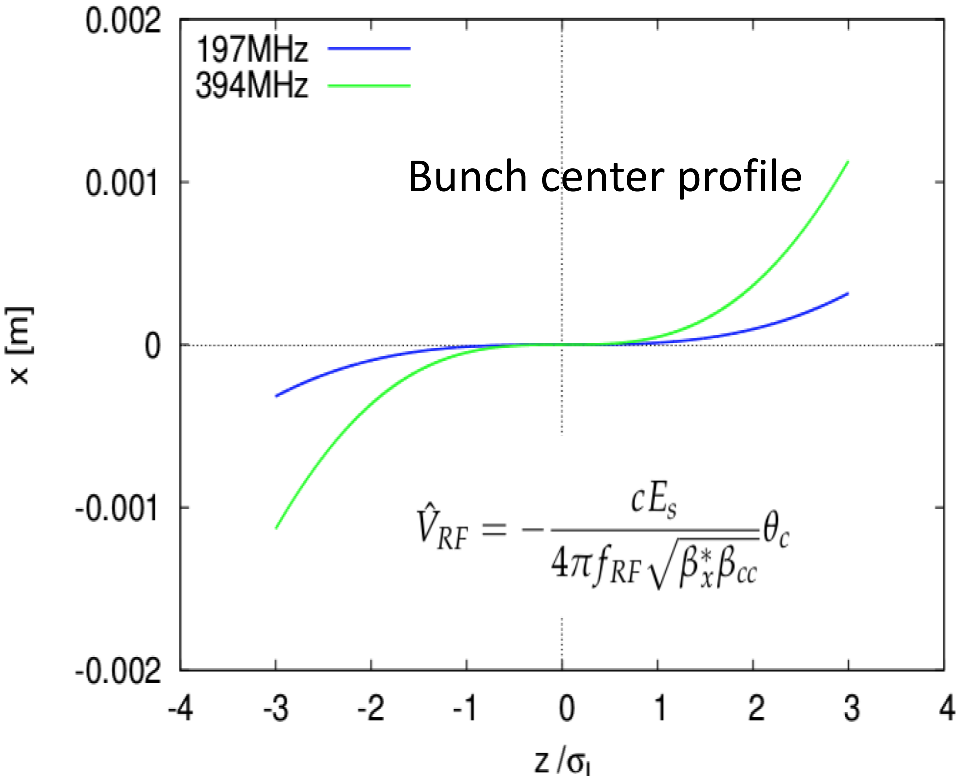
Both bunches are treated by macro-particles. Need Poisson solver to solve beam-beam force.

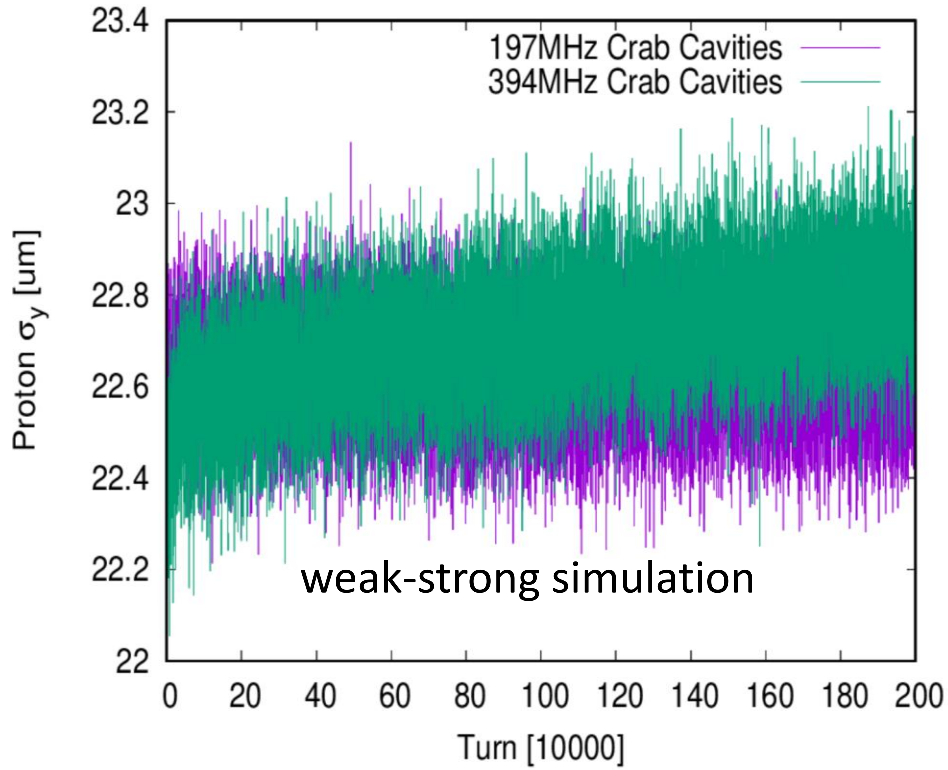
**Codes: BeamBeam3D, BBSS, SimTrack**



# Proton crab cavity frequency choosing

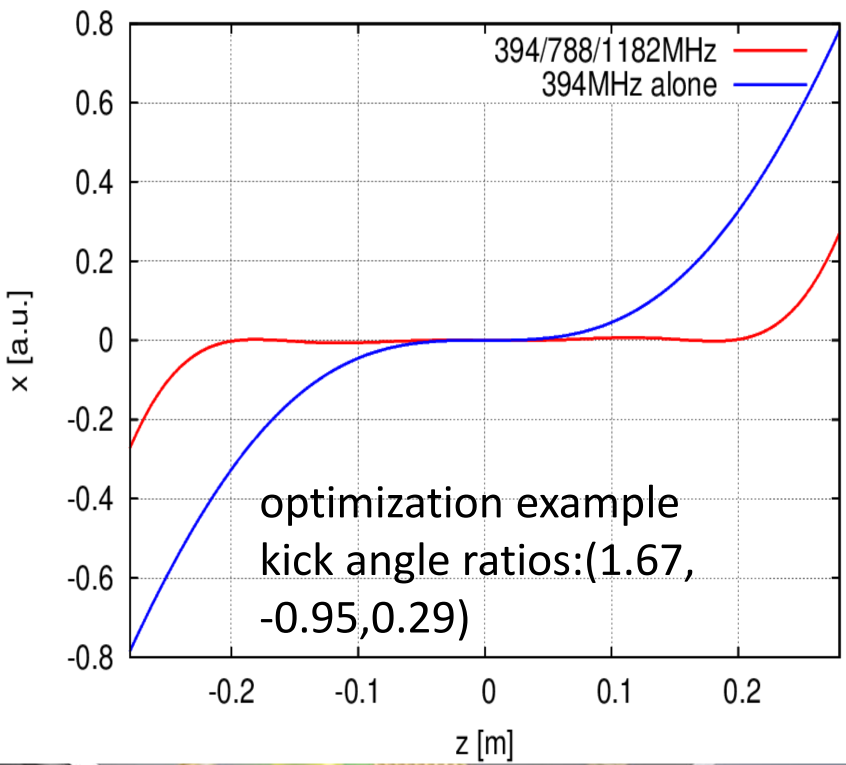
- LHC-HL adopts 400MHz CC. Technically it is preferable for eRHIC to choose 394MHz CC for both rings so that we can benefit from CERN's experiences.
- However, both weak-strong and strong-strong simulations showed that 394MHz CC in the proton ring gives much larger emittance growth than that with 197MHz.



# Combination of high RF harmonics

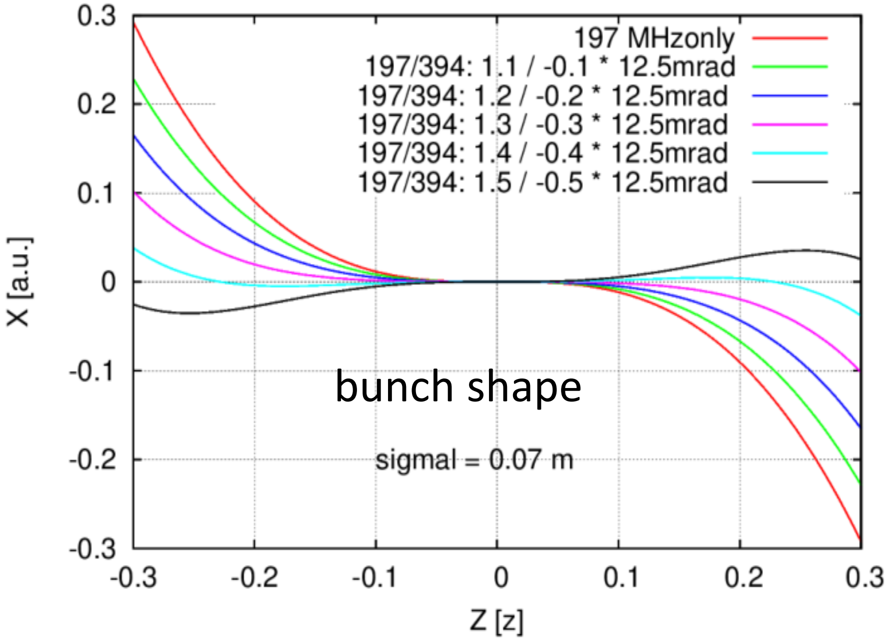
- 197 MHz CC needs more R&D than 394MHz, and its size is much larger. Another thought is to have 394MHz and its higher harmonic cavities.
- Both weak-strong and strong-strong simulations showed that to reach the same level of emittance growth rates with 197MHz alone, up to 4th harmonics CC are needed ( 394, 788,1182, 1576MHz ).




Weak-strong simulation results

| Case | $\frac{\Delta\sigma_x}{\sigma_x}$ | $\frac{\Delta\sigma_y}{\sigma_y}$ | $\frac{\Delta L}{L}$ |
|---|---|---|---|
| **(0.310, 0.305):** | | | |
| 197 | (-2.0+/-3.2)%/h | (27.7+/-9.1)%/h | (-7.6+/-3.9 )%/h |
| 394 | (9.0+/-10.3)%/h | (18.0+/-11.0)%/h | (-6.7+/-3.2)%/h |
| 394/788 | (173.1+/-27.3)%/h | (1607.2+/-81.6)%/h | (-333.1+/-13.0)%/h |
| 394/788/1182 | (2.0+/-10.0 )%/h | (69.8+/-17.)%/h1 | (-17.2+/-3.2)%/h |
| 394/788/1182/1576 | (-1.5+/-3.3)%/h | (8.3+/-4.4)%/h | (-1.0+/-1.1)%/h |
| **(0.228, 0.224):** | | | |
| 197 | (0.4/-1.6)%/h | (2.0+/-3.8)%/h | (-0.6+/-0.9)%/h |
| 394 | (23.1+/-13.3)%/h | (66.0+/-19.7)%/h | (-9.3+/-3.0)%/h |
| 394/788 | (31.9+/-17.8)%/h | (47.8+/-7.2)%/h | (-6.3+/-2.8)%/h |
| 394/788/1182 | (-1.8+/-2.5)%/h | (3.8+/-1.8)%/h | (-0.5+/-0.7)%/h |
| 394/788/1182/1576 | (0.24+/-1.4)%/h | (-0.32+/-1.2)%/h | (0.08+/-0.6)%/h |
| **(0.180, 0.175):** | | | |
| 197 | (1.4+/-2.1)%/h | (6.8+/-5.7)%/h | (-1.0+/-0.7)%/h |
| 394 | (1.3+/-4.8)%/h | (136.1+/-38.0)%/h | (-15.1+/-3.0)%/h |
| 394/788 | (14.7+/-9.7)%/h | (140.4+/-18.6)%/h | (-18.1+/-2.4)%/h |
| 394/788/1182 | (2.0+/-1.7)%/h | (42.8+/-15.4)%/h | (-4.7+/-1.3)%/h |
| 394/788/1182/1576 | (-0.4+/-4.0)%/h | (14.2+/-11.5)%/h | (-1.6+/-0.5)%/h |

# Combining 197 and 394 MHz




- A second thought: do we still need 394MHz besides 197MHz crab cavities for the proton ring ? In principle, combining both will reduce beam size growth rates.
- Both weak-strong-strong simulations showed that 197+397 MHz CC can improve the beam size growth rates by a factor of 2-3.
- In the present design, installation space for 397MHz is reserved.

weak-strong simulation results

| | Lumi (%/hour) | Sigmax (%/hour) | Sigmay (%/hour) |
|---|---|---|---|
| Single frequency | | | |
| 197MHz Only : | -0.5+/-1.5 | 3.4+/-5.9 | 0.3+/-6.1 |
| 394MHz Only : | -11.3+/-1.5 | 43.3+/-24.1 | 64.1+/-24.4 |
| combined both | | | |
| (1.1, -0.1) : | -0.8+/-1.1 | -0.002+/-2.8 | 1.9+/-4.6 |
| (1.2, -0.2) : | 0.1+/-0.5 | 1.3+/-1.8 | -1.3+/-4.6 |
| (1.3, -0.3) : | -0.01+/-0.6 | -0.9+/-1.9 | 1.0+/-3.4 |
| (1.4, -0.4) : | 0.1+/-0.3 | 0.1+/-0.9 | -0.05+/-2.1 |
| (1.5, -0.5) : | -0.4+/-0.2 | -0.6+/-2.7 | 2.7+/-1.7 |

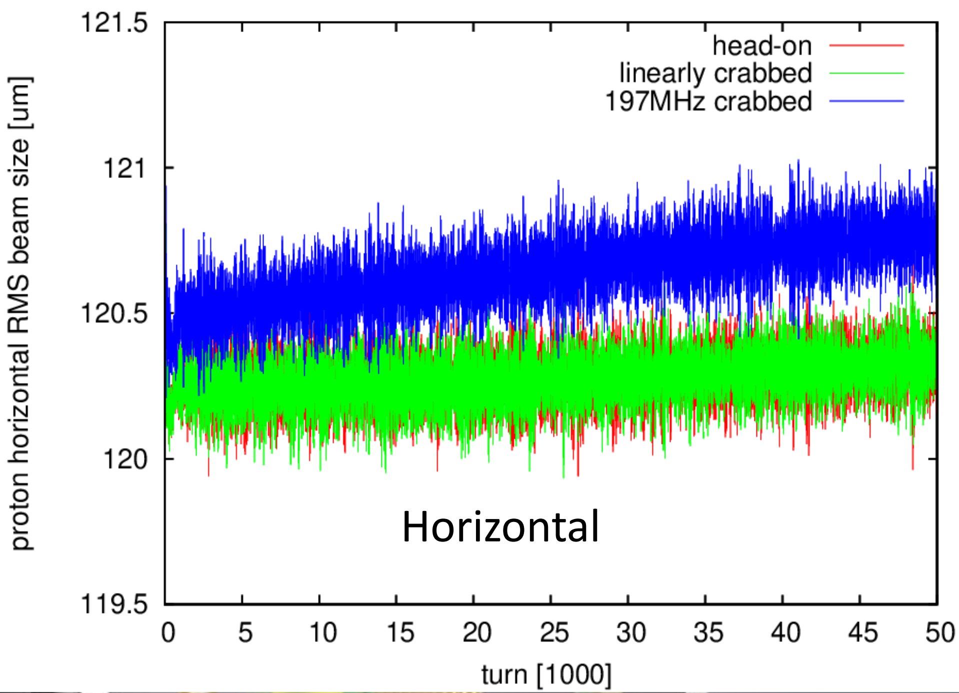
# Head-on and linearly crabbed collisions

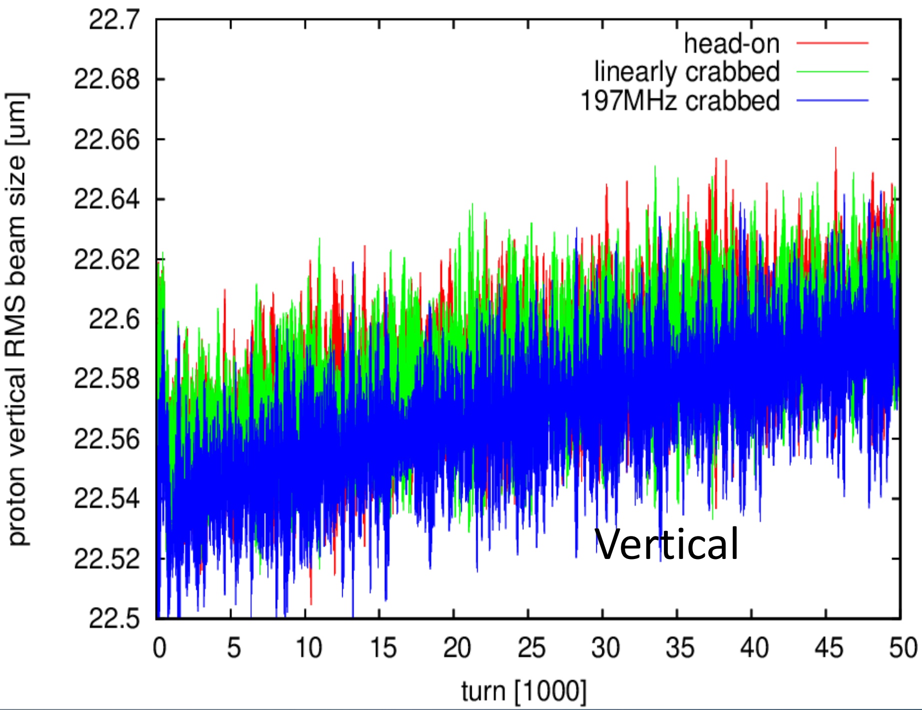
With perfect artificial linear crabbing, the same emittance growth rates and luminosity degradation rate are observed as those with head-on collision case. Therefore, the exact emittance growth is linked to crabbing.

Linear crabbing:

$$\begin{aligned}\Delta p_x &= -Kz \\ \Delta\delta &= -Kx \\ K &= \tan(\theta)/\sqrt{\beta^*\beta_{cc}}\end{aligned}$$

From strong-strong simulation

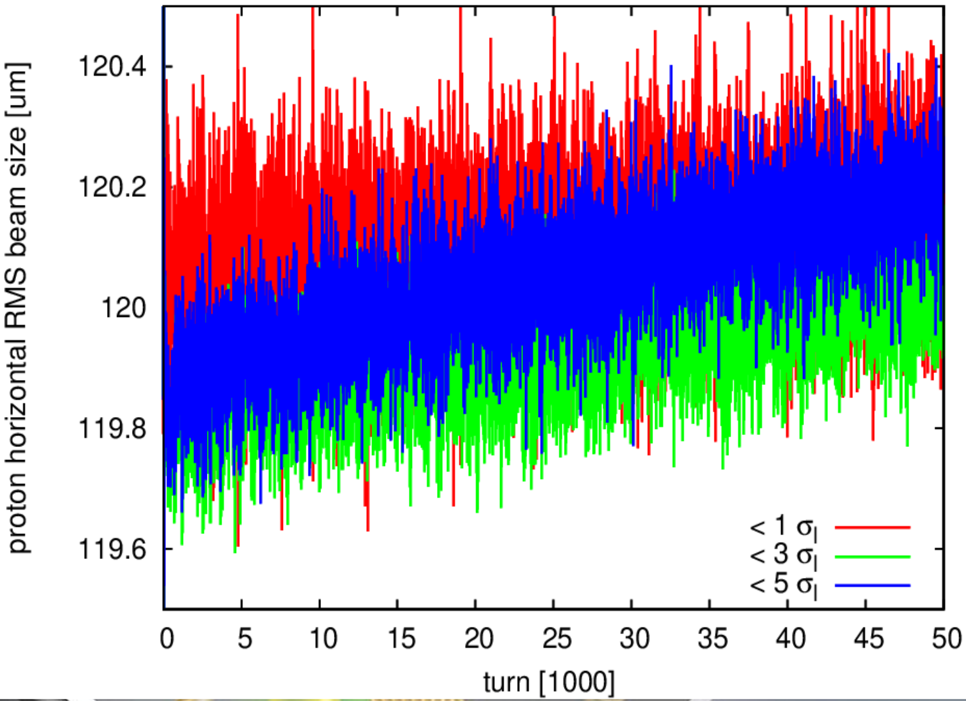


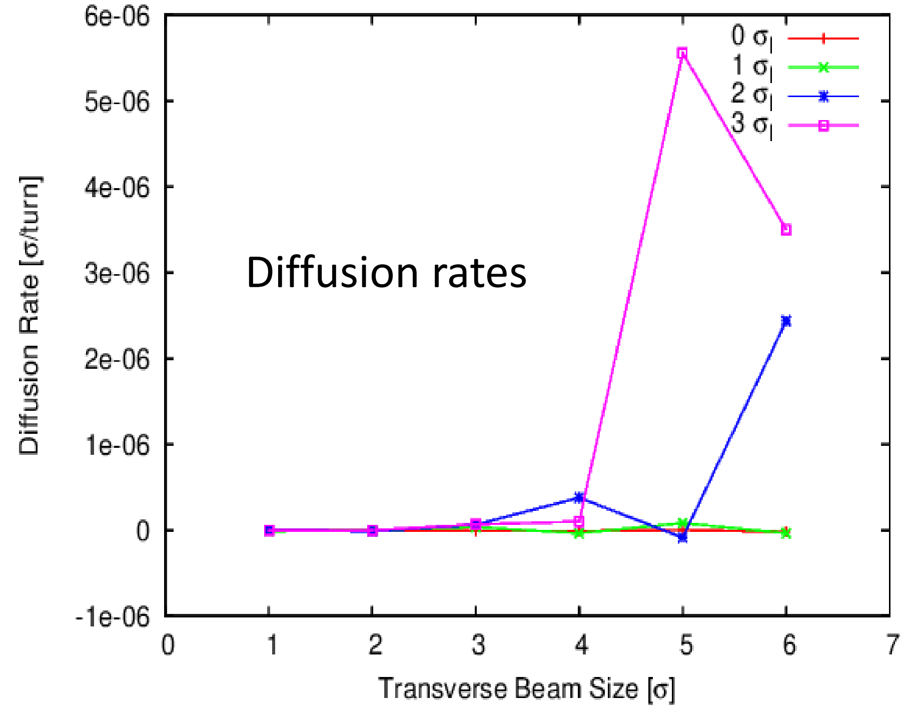
# Which particles contribute emittance growth with crabbed collision

Both weak-strong and strong-strong simulations proved that protons in the bunch tails have a larger amplitude growth rate than those at bunch center.

Strong-strong simulation



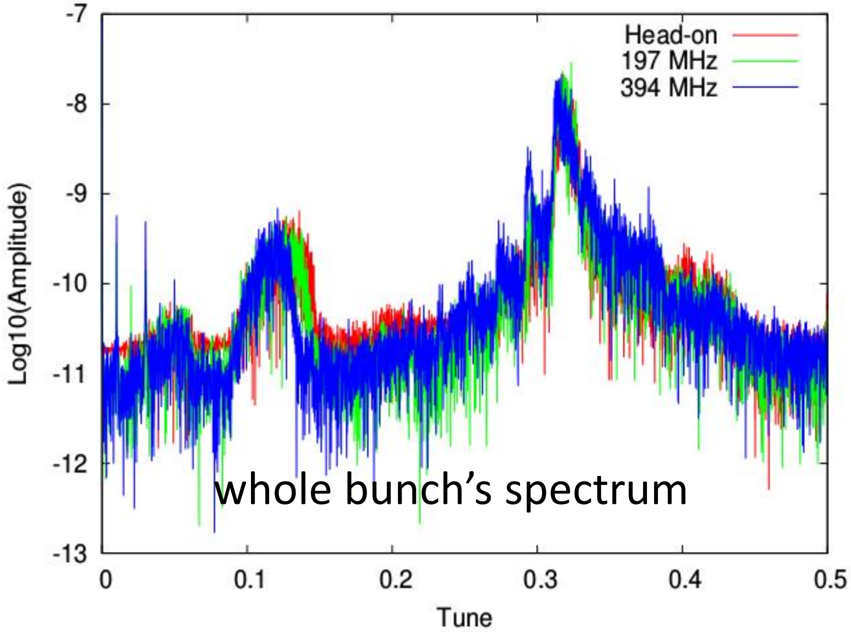

weak-strong simulation

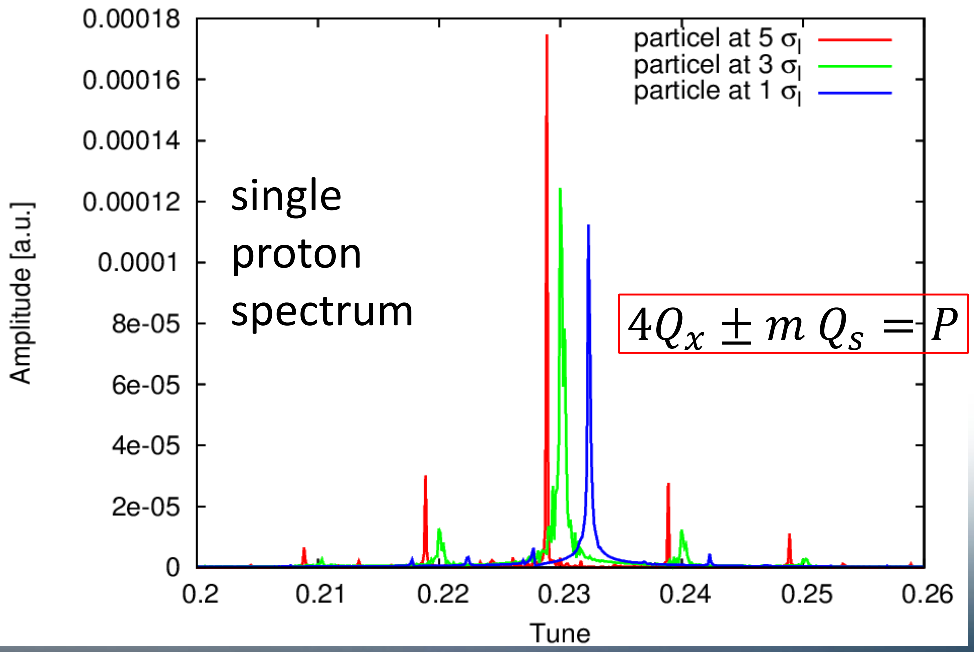


# BB introduces synchro-betatron resonances with crabbed collision

- Strong-strong simulation: from spectrum of proton horizontal motion, peaks at multiples of proton longitudinal tunes are visible, while they are missing in the head-on collision.
- Also in strong-strong simulation, test particles with different initial longitudinal action are launched. The spectrum of their horizontal motion shows synchro-betatron resonances too.

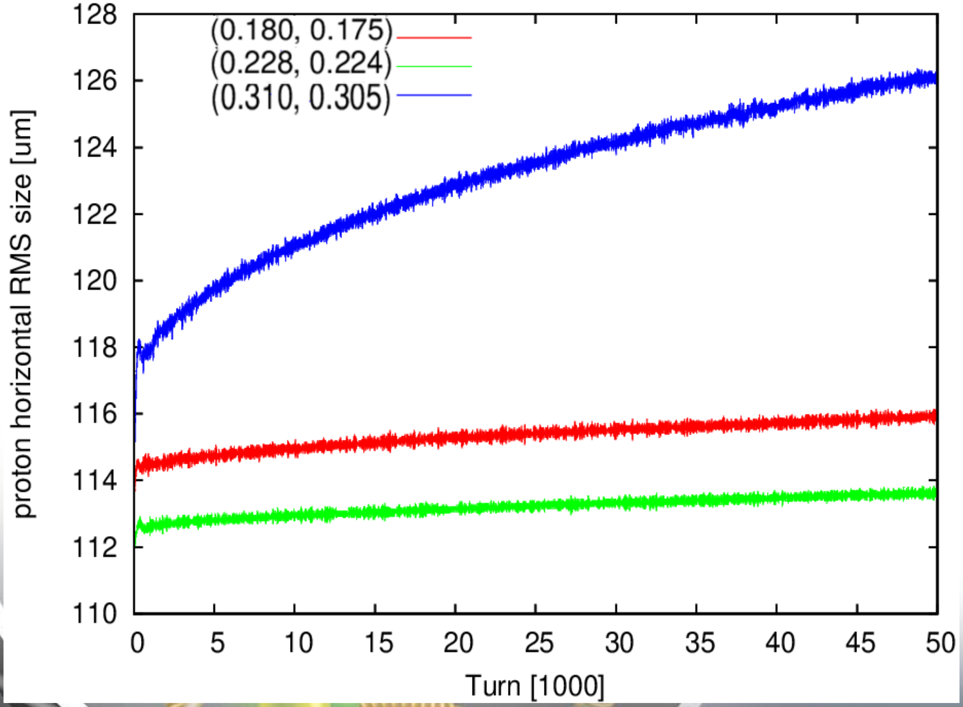
Both plots are from strong-strong simulation



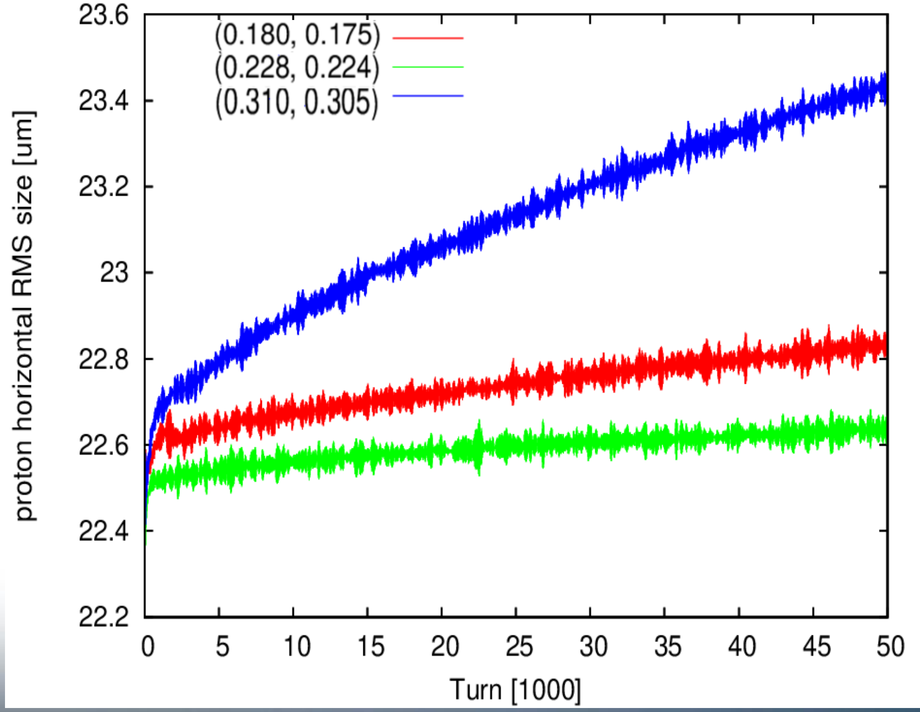



# Dependences of emittance growth rates

- Dependences of emittance growth were studied: bunch intensities, crossing angle, bunch length, crab cavity frequency, proton longitudinal tune, proton transverse tunes, electron transverse tunes, and so on.
- The goal of parameter scan is to find an optimum parameter setting to achieve minimum beam size growth rates.



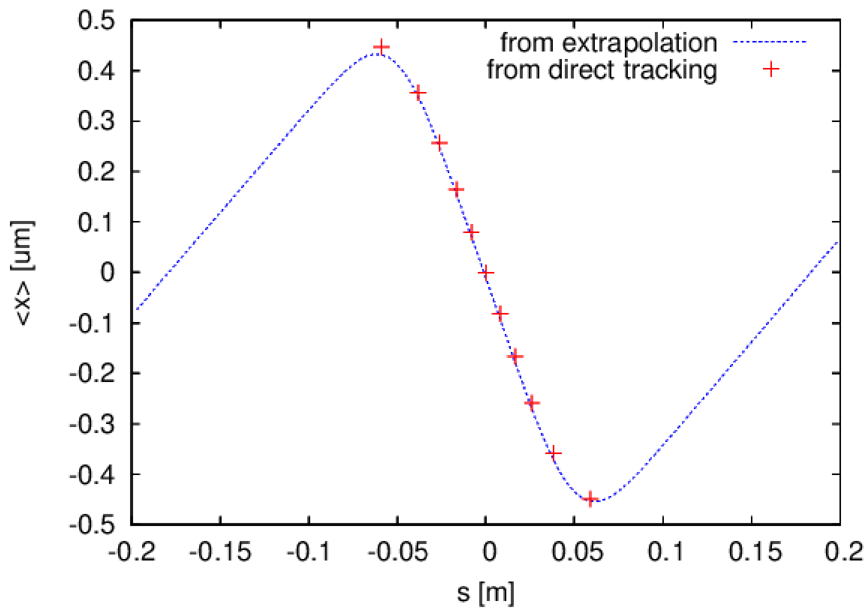

Example: proton tune scan

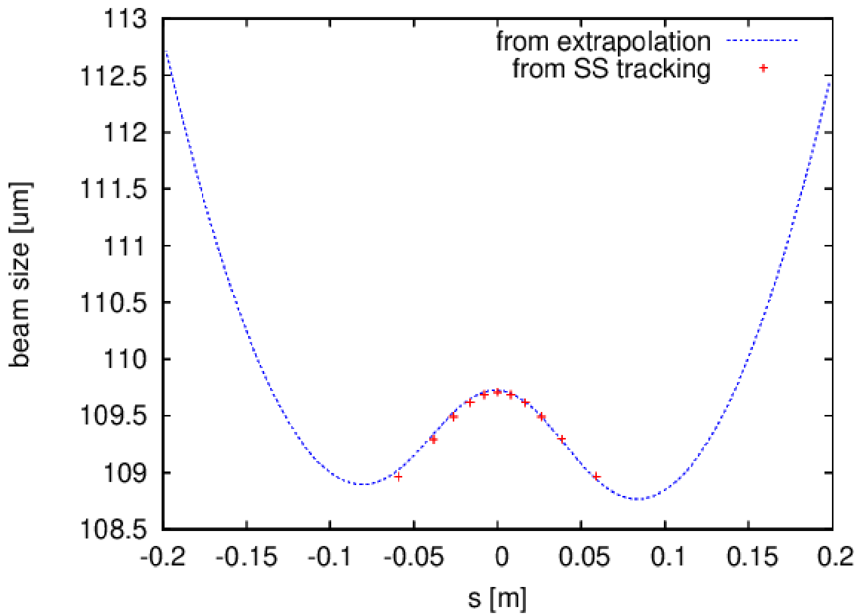


# Incoherent and coherent effects

- There are about order of 2 difference in the calculated beam size growth rates between weak-strong and strong-strong beam-beam simulation.
- We would like to know what is the main cause for beam size growth: incoherent effect,  coherent effect, or both.
- One approach is: modified weak-strong simulation.  Weak-strong tracking with equilibrium electron beam positions and sizes from strong-strong.

Equilibrium position and sizes of electron bunch



# Summary & Outlook

- ❑ Progresses made in all fronts of beam-beam simulation study for eRHIC in last year.
- ❑We did enormous simulations to verify related eRHIC design parameters and updated pre-CDR.
- ❑Had much deeper understanding of the physics behind the emittance growth with crabbed collision.
- ❑Implemented new simulation algorithms and developed new simulation codes.
- ❑Continue working on separating real beam size growth from numeric noises. Continue working on beam size growth mechanism.